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HIGH TEMPERATURE MULTIAXIAL CREEP TESTING OF NIMONIC 115

by

L. W. Candler

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A high temperature multiaxial testing facility has been commissioned using the nickel-base alloy Nimonic 115 and the difficulties associated with this technique for testing highlighted.

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HIGH TEMPERATURE MULTIAXIAL CREEP TESTING OF NIMONIC 115

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SUMMARY

Materials in present day gas turbine components are known to operate under complex stress situations. In recent years much effort has been devoted to quantifying the state of stress in multiaxial geometries and to studying the deformation and rupture mechanisms involved. Little attention has however been paid to the practical aspects of multiaxial testing and to understanding the material behaviour under complex stress states.

A high temperature multiaxial testing facility has been commissioned using the nickel-base alloy Nimonic 115 and the difficulties associated with this technique for testing highlighted.

1 INTRODUCTION

Materials in many gas turbine components operate under complex stress situations. These multiaxial stresses may arise from rotation, such as the radial and tangential stress in discs; from the action of uniaxial or biaxial loadings on stress raisers such as fir-tree roots and bolt holes; or through the superposition of stressing modes as with the centrifugal and bending forces on blades combining with loads due to temperature variations.

In the past it has been sufficient to make relatively simple assumptions in order to account for the effects of complex stresses. However, with component temperatures in operational gas turbines now exceeding 1000°C, the main concern for the design and analysis of the component behaviour is that of the materials time dependent behaviour.

When metals are subjected to creep in engineering service it can be presumed that a multiaxial stress is imposed. If the wrong stress component or stress function is used in forecasting fracture life an error as large as 10:1 has been shown to be possible. This explains the requirement for engineers to study the influence of the stress system with the objective of evolving predictive techniques which may be utilized in the design of components. Much of the earlier studies are summarized in the Johnson

Memorial Volume[1], and much of Johnson's own pioneering work, which began in the early 1930s, is summarized in one joint publication[2].

Johnson *et al*[2] have shown that the primary and secondary creep resistances of a number of pure metals and engineering alloys in uniaxial tension and under complex stress systems are identical when the metals are analysed in terms of the Von Mises effective stress, $\bar{\sigma}$, and, $\bar{\varepsilon}$, defined respectively as

$$\bar{\sigma} = \sqrt{0.5}\left[(\sigma_1 - \sigma_2)^2 + (\sigma_2 - \sigma_3)^2 + (\sigma_3 - \sigma_1)^2\right]^{1/2}$$

and

$$\bar{\varepsilon} = \sqrt{0.6}\left[(\varepsilon_1 - \varepsilon_2)^2 + (\varepsilon_2 - \varepsilon_3)^2 + (\varepsilon_3 - \varepsilon_1)^2\right]^{1/2}$$

where σ_1 , σ_2 and σ_3 are the principal applied stresses and ε_1 , ε_2 and ε_3 are the principal strains.

Much effort has been devoted in recent years to quantifying the state of stress in multiaxial specimen geometries and to studying the deformation and rupture mechanisms and their dependence upon the stress state. However, little attention has been paid to the practical difficulties and limitations associated with multiaxial testing. This may be contrasted to the situation that exists for uniaxial testing, which is covered by national standards, due in large to the historical dependence of design procedures on reliable uniaxial data. In the future, increasing importance will be attached to multiaxial data and it is essential that testing techniques are soundly based on theory and are adequately controlled. It is also important to develop simplified techniques which may be used to generate the required volume of data economically.

Although the creep behaviour of metals has been investigated since the early twentieth century, little data is available to describe this phenomena for the case of non-proportional variable loading conditions. The vast majority of testing being performed under constant uniaxial load conditions does not necessarily describe those conditions encountered in real components which operate under variable and complex states of stress. Such simplistic loading conditions do not show many of the effects found under complex stress states and so because modern design requirements for components used in aerospace, nuclear and chemical industries, for example, there is now a requirement for greater knowledge of material behaviour and the formulation of credible material models.

In order to fulfill this requirement it is necessary to obtain results of creep tests for complex stress states and variable loadings. Such experiments to date have been very limited and until relatively recently, due to technical difficulties in experimentation, have not been performed in a systematic way. Tests have been carried out basically for plane stress conditions ($\sigma_1 \neq 0$, $\sigma_2 \neq 0$, $\sigma_3 = 0$) using different test techniques and assuming that creep rupture is controlled predominantly by the octahedral (Von Mises) shear stress.

2 MACHINE AND SPECIMEN DESIGN

The objective of this program was to commission a high-temperature multiaxial testing facility such that both the limitations and problems associated with this type of testing are overcome and useful data obtained from a small test matrix.

2.1 The tension-torsion testing machine

The tension-torsion testing machine was developed and built by Dartec Ltd and consists of a load frame, hydraulic power supply, system control cabinet and a Texas micro-computer. The load frame is capable of applying tensile or compressive axial loads and forward/reverse torsional load under both static and dynamic conditions. It is capable of through zero loading and has a rated capacity of ±100 kN and ±250 Nm.

The torsional actuator is capable of rotating through 200° (100° either side of zero) and the axial actuator has a full stroke capability of 100 mm. The control cabinet is capable of controlling the load frame and of processing load, extension and position signals. The cabinet is fitted with electronic units for the servo-amplifier control, transducer signal conditioning, function signal generation, signal level display and output, limit detection and tripping, hydraulic pump control and total system shut-down and is directly linked to the micro-computer allowing for the remote setting up and operation of the load frame. It also allows complex loading waveforms to be performed through the relevant software and provides a means of processing and storing output test data.

2.2 Specimen design

Due to the requirement for both uniaxial and multiaxial creep data two types of specimen were tested; both types of specimen being machined to RAE(P) designs namely:

STD 3651/A (Ref Fig 1a) Uniaxial creep specimen

STD 5015 (Ref Fig 1b) Multiaxial test specimen

In order to allow for a sensible degree of angular twist to be applied to the multiaxial test piece, when subjected to a torque loading, a hollow specimen with a 1 mm wall thickness and a gauge length of 40 mm was chosen. The conical ends of the test piece provide location and allow for self alignment within the pull-rods of the load frame.

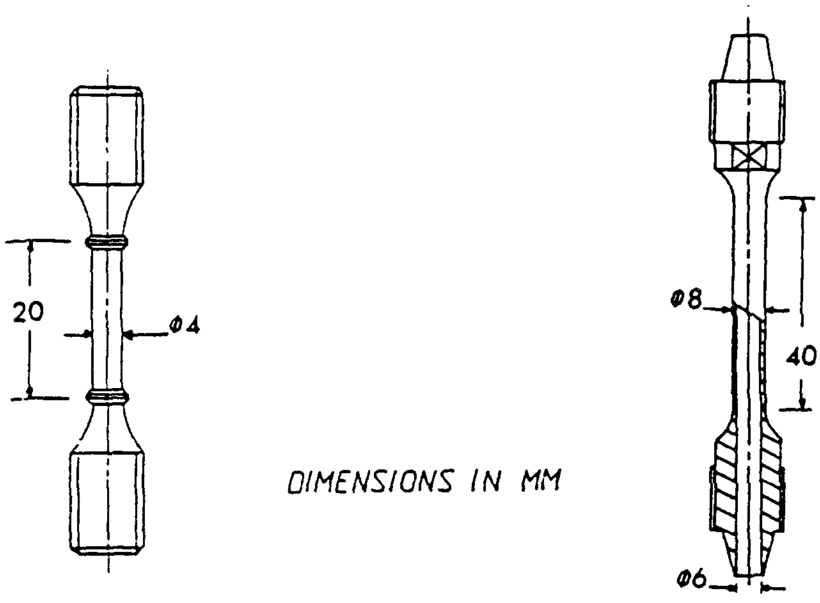

Fig 1a Uniaxial creep specimen Fig 1b Multiaxial creep specimen

Nimonic 115 bar stock was used throughout for test piece manufacture, the bar being cut into suitable size blanks which were heat treated as described below prior to the machining operation.

The alloy blanks were subjected to the following three stage heat treatment:

(i) Solution treatment, 1.5 hours at 1190°C then air cool.

(ii) An ageing treatment, 1100°C for 6 hours and air cooled.

(iii) Final ageing at 850°C for 16 hours and air cooled to ambient.

2.3 Specimen gripping arrangement

The specialised gripping arrangement (pull-rods) consist of four parts (Ref Fig 2), these being:

(i) Pull-rod shaft

(ii) Clamping ring

(iii) Actuator flange

(iv) Specimen lock nut (not shown in figure)

Parts (i) and (iv) are machined from Nimonic 105 allowing high temperature testing to be performed. Parts (ii) and (iii) are machined from stainless steel. The pull-rod shaft has a stump below the flange in

order to provide good location on the actuator and also allow the complete assembly to be rotated during specimen loading and machine set-up. The clamping ring provides a means of holding the pull-rod shaft tight on the actuator flange which in turn is fixed onto the machine actuator. One complete assembly is fitted to each of the load frame actuators. A method of cooling the pull-rod shafts is required at the temperatures being considered and this is provided by a constant flow of water (approx 100 l/hr) passing through a water cooling jacket (top) a cooling block (bottom). A high temperature trip has been fitted to the testing machine preventing overheating of the pull-rods should the cooling water supply fail.

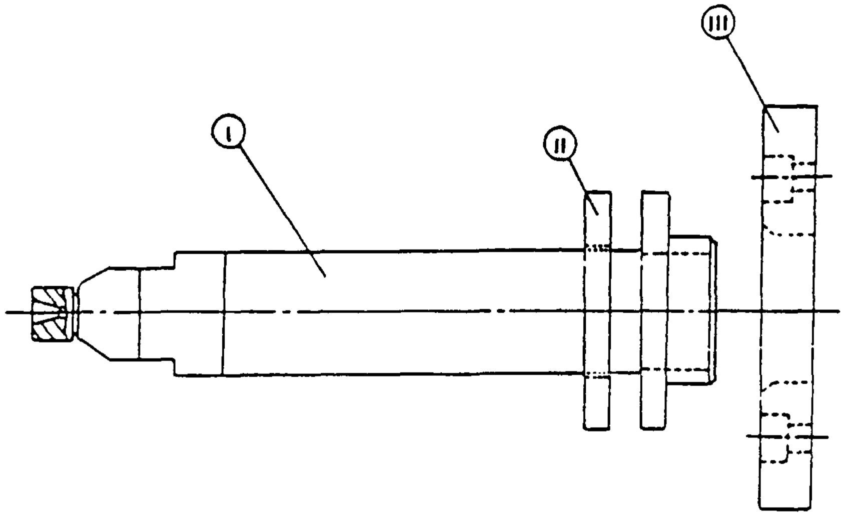

Fig 2 Multiaxial pull-rod arrangement

2.4 Temperature control

The specimens are heated by a three zone split radiant furnace manufactured by Severn Science Ltd. The furnace is in turn controlled by a Eurotherm temperature controller. In order to record the temperature gradient along the specimen gauge length three platinum - 13% rhodium-platinum thermocouples are attached to the specimen and their output recorded on a multichannel chart recorder. The furnace is calibrated such that a temperature gradient of ±3°C or better is attained along the specimen gauge length.

3 PROCEDURE

In order to gain some understanding of the behaviour of Nimonic 115 when subjected to multiaxial stress conditions, the behaviour of the material when undergoing both tensile and torsional loadings must first be studied. In order to satisfy this requirement a short test matrix was devised in which a number of tensile and torsional creep tests were to be performed at two temperatures. Once completed, a suitable tension-torsion test matrix consisting of various ratios of tensile loading to torsional loading, for a fixed Von Mises stress, was devised for each of the test temperatures.

In order to assess the compatibility of results between the constant stress creep machines and the constant load tension-torsion machine comparative tests were performed as a cross check. The results were considered to be within acceptable experimental agreement.

4 RESULTS

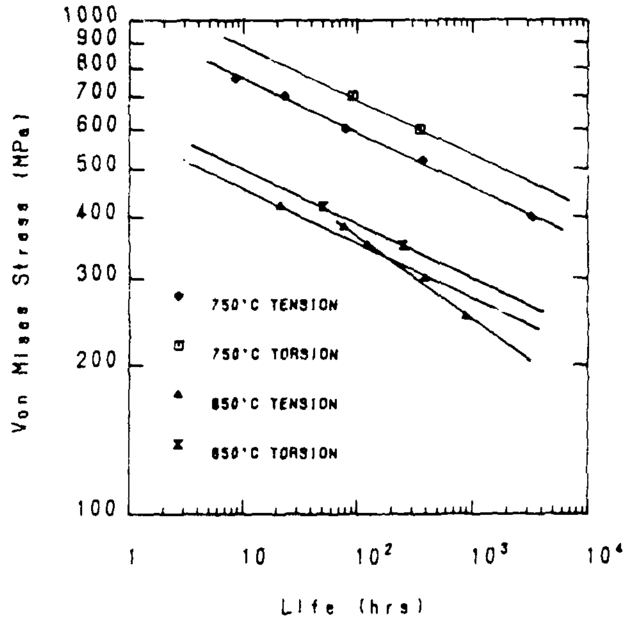

Fig 3 Stress-rupture curves for tensile and torsional loadings

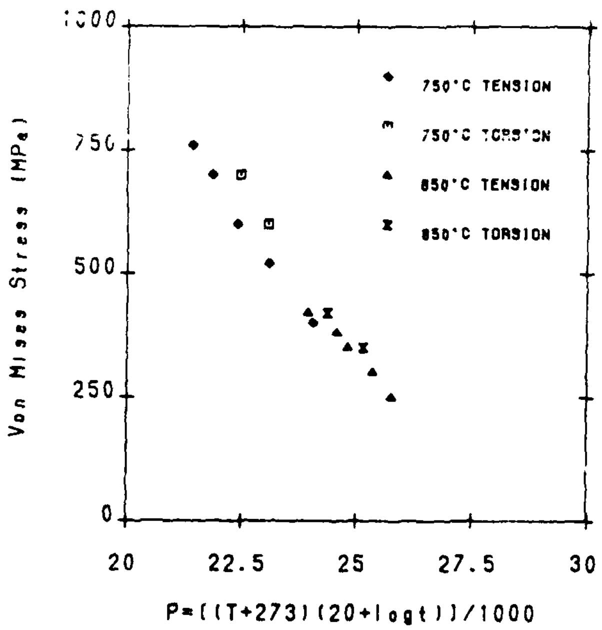

Fig 4 Larson Miller parameter for tensile and torsional loadings

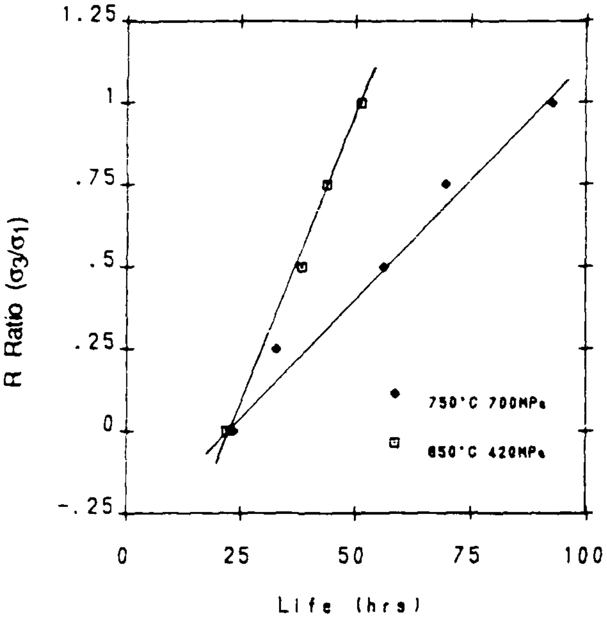

Fig 5 Multiaxial creep showing the effect of R-ratio and temperature

5 DISCUSSION

The subject of high temperature multiaxial creep behaviour has only recently been seen as an inherent problem for the gas turbine manufacturers and designers. The complexity and intrinsic uncertainty in design technique is considerably increased when the high temperature fatigue process if further complicated by the time dependent phenomenon of creep.

Much effort has been devoted in recent years to quantifying the state of stress in multiaxial geometries and to studying the deformation and rupture mechanisms and their dependence upon stress state[3,4]. However, tnese are all theoretical approaches to the problem and little if any attention has been paid to the practical difficulties of multiaxial testing. This can be reflected in the number of publications available on the subject in comparison with the numbers available on the subject of uniaxial behaviour at high temperatures. Although very limited, some research into the effects of pure torsional loading on thin walled cylindrical specimens has previously been undertaken[5,6].

Since the development of elevated-temperature alloys and the design of components cannot wait for many years' duration, methods of extrapolating short-term test data are of great importance. The direct approach in attempting to extrapolate creep or rupture data is to obtain the data for as long a time as possible and then to extrapolate the curves for the longer term data.

Analysis of the data obtained during this test program brought forward a number of interesting points. The plots of stress against rupture life, Fig 3, showed the torsional creep lives to be greater than those for

tensile creep at the same Von Mises stress. This was not totally unexpected and may be explained by the fact that strain in torsion is accumulated more slowly than strain in tension at the same effective stress, and hence the onset of tertiary creep is slowed down in torsion.

A plot of most creep data takes a considerably more linear appearance when one or both scales are logarithmic. It can therefore be tempting to use this approach as an aid to extrapolation. However, there is a loss of accuracy of estimation when reading points off a logarithmic scale. There is also a more serious objection to extrapolation, that is the unexpected changes which may occur at longer times. For example, stress-rupture data for short rupture lives often plot as a straight line. At longer times and higher temperatures the plots may show pronounced curvature or a break in the straight line and the rupture life may be considerably shorter than that obtained by extrapolation of short term data.

The method of extrapolation can be improved by the use of various parameters to combine the creep rate or rupture life with temperature. Extrapolation is then based upon a plot of this parameter as a function of stress. To correlate the combined effects of temperature T and rupture life t_f, a parameter often used is one proposed by Larson and Miller(7) that is $T(C + \log t_f)$. The value of C being material dependent, in this case, for Nimonic 115, it is equal to 20.

The Larson Miller plot obtained from the tensile and torsional creep data, Fig 4, exhibits good correlation between temperatures and allows a reasonably accurate estimate of rupture life to be made for any untested stress and temperature within the range plotted.

These analysis techniques however have their limitations. The stress-rupture plots can lead to inaccurate estimations being made by assuming a degree of linearity in the results outside the region of data, whereas the Larson Miller approach should only be used for interpolation. Although of some use for the estimation of pure tensile or torsional results neither of these techniques can be used to predict the effect of combined loading simulations. A plot of R-ratio against temperature goes some way to illustrating these effects, Fig 5, assuming that multiaxial creep follows a linear form. For the data available it can be seen that an approximation towards this linearity is feasible, however a distinct temperature dependence is shown by the differing slopes of these plots. The effect of stress dependence under these multiaxial loadings is still to be investigated.

Ideally, some technique for modelling the creep behaviour of a material under complex stress situations must be developed. In order to develop such a model some knowledge of the materials behaviour at a variety of conditions must be obtained and now that techniques are available to obtain this data the first steps towards developing a credible model can be made.

6 CONCLUSIONS

Despite the inherent problems associated with the practicabilities of high temperature multiaxial testing, the experience and knowledge gained

has been of immense value. The results can be summarised into four major achievements:

(i) A prototype testing machine has been commissioned such that a variety of test conditions can be performed in axial, torsional or multiaxial loading modes, at elevated temperatures (up to 1000°C), with confidence in the results obtained.

(ii) Ideas for a suitable specimen were taken from the design stage, developed and tested under a number of conditions. The limiting factors of the design have been highlighted and hence modifications can be made to the initial design in order to develop the specimen design for use in future test programs.

(iii) A technique for performing the actual tests has been successfully developed. It is not just a case of gripping a piece of metal and 'twisting' and 'pulling'. The specimen has to be loaded into the testing machine in such a way that it remains aligned, between the pull-rods, and in an unstressed state at zero load. Calibration of the furnace and controllers has to be maintained and checks made at regular intervals, in order to satisfy the requirement for a temperature gradient of ±3°C across the specimen. Most importantly, the correct test conditions must be applied, and maintained throughout the duration of the test, and suitable records for the test variables obtained.

(iv) The applicability of the Von Mises approach has been investigated but further work is required in order to validate this approach.

The door into the field of multiaxial testing has certainly been opened and although the subject is, on the whole, still in its infancy the first few steps towards understanding material behaviour under multiaxial creep have been made The basic techniques for testing, which until now have been major stumbling blocks, have been conquered. High temperature multiaxial testing can now be performed with a reasonable degree of confidence, all that can be done now is to exploit its potential, improve the practical aspects involved and increase our understanding of the subject.

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17. Abstract

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